



THE MINISTRY OF NATIONAL INFRASTRUCTURES  
GEOLOGICAL SURVEY OF ISRAEL

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**Ezra Zilberman, Hagai Ron, Ron Sa'ar**



Submitted to the Inter-ministerial Steering Committee for Earthquake Preparedness

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**Cover:** A westward view on the Ahihud Ridge. In the front - the upper surface of the colluvial apron at Har Gamal site



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# **Evaluating the potential seismic hazards of the Ahihud Ridge fault system by paleomagnetic and morphological analyses of calcretes**

**Ezra Zilberman<sup>1</sup>, Hagai Ron<sup>2</sup>, Ron Sa'ar<sup>2</sup>**

1. Geological Survey of Israel
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## **Abstract**

The present study examined the Ahihud Ridge Fault System, in order to evaluate the seismic hazards it may pose to northern Israel.

We examined the two NW oriented Judeida faults and the eastern exposed part of the E-W oriented Ahihud fault, using pedogenic calcrete units dated by paleomagnetic methods as markers for identifying young tectonic activity or long-term stability along these faults.

The northern Judeida fault, that elevated the Har Gamal block, has been stable at least since the Middle Pleistocene but most probably since earlier periods. This is evident by a sequence of two colluvial units, attached to the Har Gamal southern tectonic slope, each cemented by mature (stage IV-V) calcrete, with a normal magnetic signal. The trace of the southern Judeida fault is covered by an un-deformed mature (stage IV-V) calcrete crust 2-3 m thick with a normal magnetic signal, indicating tectonic stability at least since the Middle Pleistocene.

The eastern most tip of the Ahihud fault is covered by an un-deformed thick, mature (stage IV-V) calcrete with a normal paleomagnetic signal. However, a short distance to the west, the calcrete seems to be displaced by the fault, and a fresh, calcrete-free slope marks its trace. Further westward, along the coastal plain, this fault bounds the Hillazon Graben, where evidence for 80 m of Pleistocene subsidence was found.

A coastal abrasive surface of the Pliocene-Early Pleistocene Kurdani Formation, found along the western part of the Ahihud Ridge at an altitude of 30-40 m, indicate that since its formation only a minor uplift has occurred along this ridge.

We concluded that according to the Israeli Building Instructions Code the Ahihud Ridge and the Judeida faults are tectonically stable. Although, the Ahihud fault was active after the formation of the regional calcrete cover in this region, there is no time constraint on its young activity. Therefore, it is recommended to trench the fresh escarpment of the Ahihud fault in order to examine if it is of tectonic or artificial origin. If this scarp is of tectonic origin, a paleoseismic study is required in order to shed light on the tempo of the Pleistocene activity along this fault.



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## **1. Introduction**

The Ahihud fault system (AFS), located in the north of Israel, extends from the Bet Kerem tectonic valley in the east (Kafri and Ecker, 1964) to the Mediterranean shelf in the west (Eytam and Ben Avraham, 1992; Sivan and Galilee, 1999; Sade, 2006). It consists of three faults: Judeida north, Judeida south and Ahihud, which are associated with a prominent structural and topographic ridge in the eastern part of the system. This fault system was considered to be a potentially active fault by Bartov et al. (2002), and as an active fault by Sivan (1996) and Sivan and Galilee (1999).

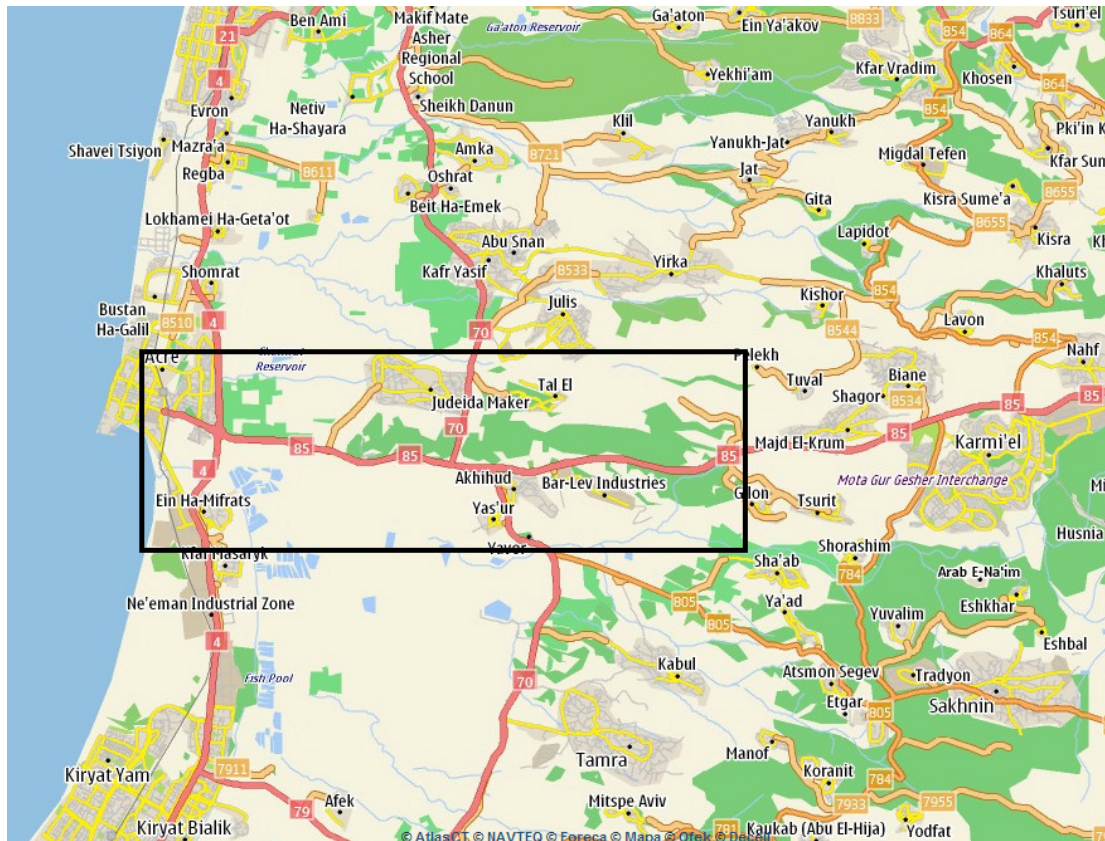
The purpose of the present study is to collect additional surface and subsurface data in order to evaluate the seismic hazards that this fault system poses to northern Israel.

## **2. Geographic and topographic setting**

The AFS is the western extension of the Bet Kerem tectonic valley and its associated faults (Matmon et al., 2000). The Ahihud structural ridge is separated from the northern tectonic escarpment (the Zurim escarpment) of the Bet Kerem valley by the abandoned stream valley of Nahal Itzhar. This stream was an ancient outlet of the Bet Kerem drainage system (Kafri, 1997; Matmon et al., 2000). Its upper drainage basin was captured by Nahal Shagor that drains to the lower Hillazon Valley through a narrow canyon incised between the high (372 m.a.s.l.) Har Gilon ridge in the east and the lower Givo't Ahihud hills (122 m.a.s.l.) in the west (Fig 2). Nahal Itzhar drains the northern part of Ahihud Ridge, which developed along the Ahihud fault system. This ridge is about 10 km long, descending from an altitude of 324 m in Har Gamal in the east to some 70 m in the west. From Ahihud junction westward this ridge rises above the flat Zevulun Valley.

The Ahihud fault that appears for the first time in the south western part of the Ahihud Ridge (Levy, 1983; Sneh, 2006) crosses the Galilee coastal plain with no surface expression, except in the shallow shelf. In this area it forms a prominent lineament across the submarine kurkar (Aeolianite) ridges and is associated with a vertical displacement of a few meters (Eytam and Ben Avraham, 1992; Sivan and Galilee, 1999; Sade, 2006).

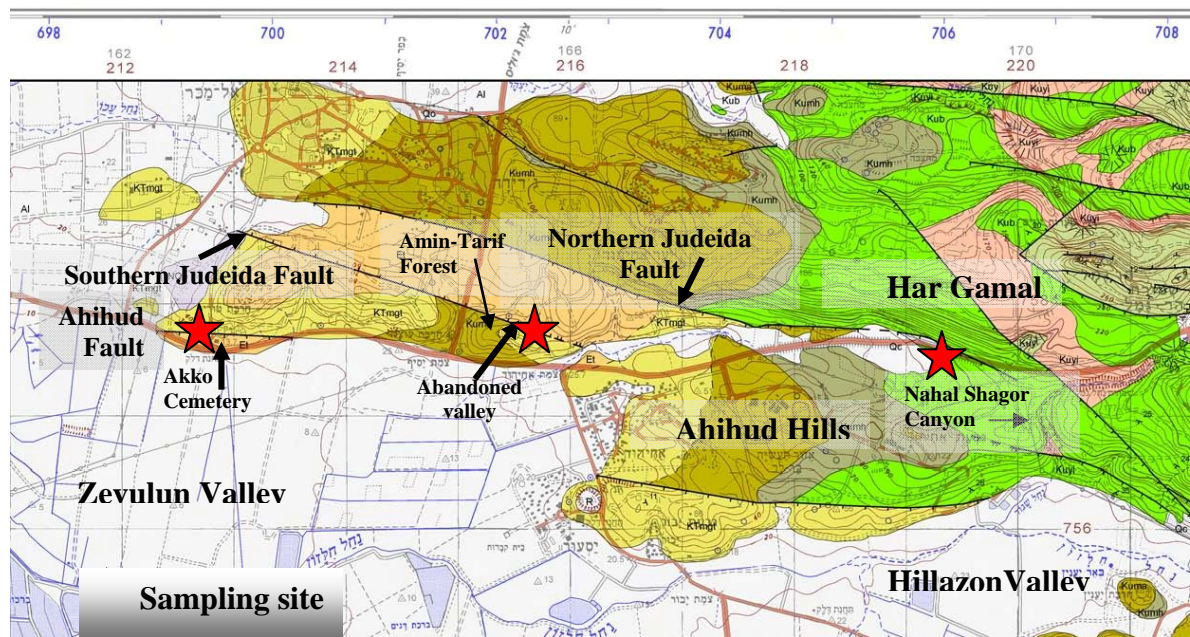
The geological map of the area crossed by this fault system was produced by Levy, (1983) and amended by Sneh (2006).



**Fig 1** - Map of the study area.

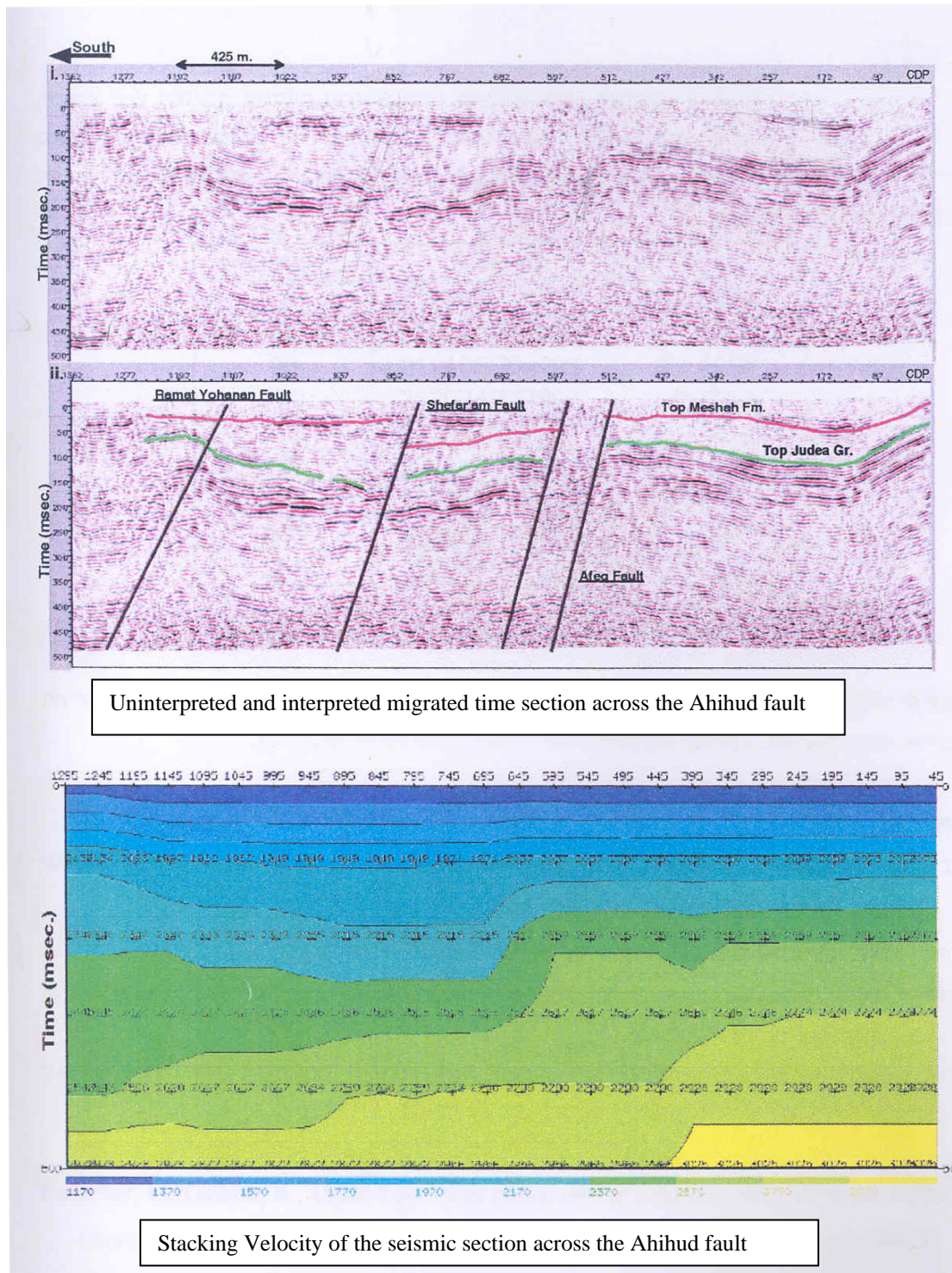
### **3. Geological background**

The AFS comprises of three main faults: The NW oriented southern and northern Judeida faults, which form a narrow Graben (the Judeida Graben) across the Ahihud Ridge and the E-W Ahihud fault (Fig 2). The vertical displacement along the eastern part of the northern Judeida fault is more than 200 m and it is associated with a tectonic scarp about 140 m high. The vertical displacement decreases to the NW to some 100-150 m in the Judeida Graben (Sneh, 2006). According to Sivan (1996), this fault can be traced across the coastal plain, where it forms the northern boundary of the Akko horst.



**Fig. 2** - Geological map of the Ahihud Ridge (Sneh, 2006). The paleomagnetic sampling sites are marked as red stars.

Sivan (1996) correlated this fault with a submarine fault scarp, exposed in the coastal shelf just north of Akko and attributed to this fault tectonic activity during the Holocene. However, a recent seismic study conducted in the eastern part of Akko (Sagi, 2010) found that the Ahihud fault splits in this area into two branches. The northern one can be extrapolated with the submarine fault, considered by Sivan (1996) and Sivan and Galili (1999) as the western extension of the northern Judeida fault. The southern Judeida fault is shorter and the maximum vertical displacement along its trace is about 150 m. There are no indications of eastern or western extensions of this fault beyond the exposed trace.



Uninterpreted and interpreted migrated time section across the Ahihud fault

Stacking Velocity of the seismic section across the Ahihud fault

**Fig. 3** - The Ahihud fault in a N-S oriented seismic line west of Makr (from Medvedev, 2006). The fault plain can be traced almost to the surface.

The Ahihud fault is exposed only along the western part of the Ahihud Ridge, where it displaces the well bedded limestone and chalk of the Eocene Timrat Formation versus the grey marl of the Paleocene Taqiye Formation (Levy, 1983; Sneh, 2006). Further westward it was detected under the coastal plain by geophysical seismic lines and drill holes (Fig 3). This fault forms the northern boundary of the wide Kishon

extensional structure and the narrower Hillazon Graben (Kafri and Ecker, 1964; Mero, 1983; Medvedev, 2005; Sagi, 2010). The post Pliocene subsidence of the Hillazon Graben is estimated by Kafri and Ecker, (1964) and Sivan, (1996) to be approximately 80 m. The creation of the barrier between the Haifa bay and the Galilee coastal plain was allocated by Sivan (1996) to the Middle Pleistocene activity (During isotopic stage 6) along the Ahihud fault. This barrier partly blocked the northward transportation of Nilotic quartz sand from the Haifa bay sedimentary province to the Galilee coast (Kafri and Ecker, 1964).

The trace of the Ahihud fault is clearly expressed in the shallow shelf, west of Akko, as a 3 km long lineament. A scarp 3-4 m high was detected along this lineament, where the southern block is subsided (Sivan, 1996; Sivan and Galili, 1999; Sade et al., 2006).

#### **4. Stratigraphy**

The stratigraphic sequence exposed along the trace of the AFS ranges from the Cenomanian to Holocene. The Cenomanian **Yanuch** and the Turonian **Bina and Yirka** Formations are exposed in Har Gamal (Sneh, 2006), but the Cenomanian **Sakhnin** Formation is missing. This discrepancy is attributed by Wachs et al (2009, 2011 submitted), to a misinterpretation of the Upper Cretaceous marine sequence of the western and central Galilee. They suggested that the Yanuch Formation is actually the upper part of the Dir-Hanna Formation, exhibiting the same lithological character, and that the missing overlying Sakhnin Formation was totally dissolved at some places by Karstic processes, especially along fault traces.

The Senonian **Menuha** Formation is exposed on the western part of the Ahihud Ridge as part of a west descending flexure. It's composed of free members; Har Zefat chalk, Kabri marl and Ahihud chalk. The Campanian Mishash Formation forms a thin discontinuous limestone bed with chert concretions. The Maastrichtian chalky **Ghareb** and the Paleocene marly **Taqiye** formations are exposed in the Judeida Graben and the western part of the Ahihud Hills. The Eocene sequence is represented here by the bedded limestone and chalk with chert concretions of the **Timrat** Formation, exposed mainly in the Judeida Graben.

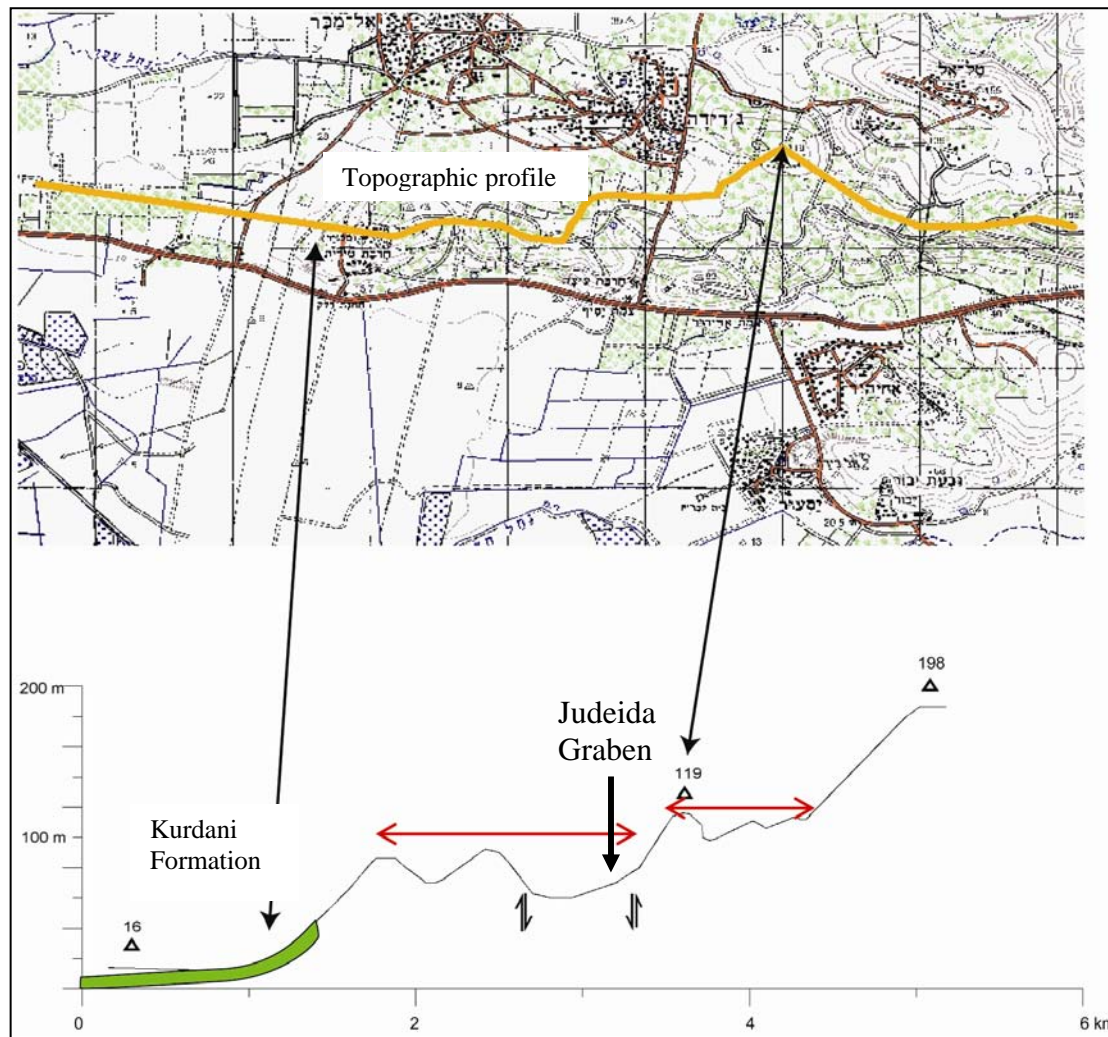
The Pliocen-Early Pleistocene **Kurdani** Formation (Picard, 1928, Kafri and Ecker, 1964; Gvirtzman, 1970) is exposed along the western margins of the Ahihud hills. It consists of littoral to coastal calcarenite with well-rounded chert pebbles embedded

into it (Fig 4). This calcarenite covers an abrasive terrace that cuts the western margins of the ridge at an altitude of 30-40 m.



**Fig. 4.** - *The coastal facies of the Kurdani Formation at the western margins of the Ahihud Ridge, consisting of calcarenite with well rounded chert pebbles.*

Further westward, the Kurdani Formation is exposed at the lower part of Tel Akko (Sivan, 1996). The maximum thickness of the Kurdani Formation along the trace of the Ahihud fault is 20-25 m and there are no clear thickness differences on both its sides (Sivan, 1996). Although the Kurdani Formation is mainly a shallow marine unit composed primarily of bioclastic limestones, in the subsurface it also contains some eolian facies (Sivan, 1996).



**Fig. 5** - The outcrop of the Kurdani Formation marked on longitudinal profile along surfaces. Two higher erosion surfaces are marked by red arrows. (From Zilberman et al., 2008).

The Kurdani Formation is overlain by the **Hefer Formation** of Pleistocene age, which was subdivided by Sivan (1996) to six members:

1. The Ness Amim Hamra Mbr.- a residual paleosol that developed upon the Kurdani Formation.
2. The Akko Kurkar Mbr. - consists mainly of coarse bioclastic limestone in the west and of eolian facies in the east. Its thickness ranges between 10-14 m. In the Akko horst it is very thin (1-2m) or completely missing (Sivan, 1996).
3. The Evron Hamra Mbr.- a sandy reddish paleosol where prehistoric tools were found. These tools are attributed to the Late Early Achulian and Early middle Achulian cultures. This unit was encountered in the subsurface all over the Galilee coastal plain. It is up to 16 m thick in some depocenters but only 4 m thick on the Akko Horst. It is exposed in the Evron and Ness-Amim quarries.

4. The Regba Kurkar Mbr – A sequence consisting of alternations of kurkar and Hamra units that builds three longitudinal low ridges sub-parallel to the present coastline. The eastern ridge (the Evron ridge) runs along the central coastal plain, the central ridge extends along the coastline and the western ridge is submerged along the shallow shelf. This kurkar is of eolian origin composed of bioclastic components (50-70%) and Quartz grains (30-50%). In the ridges it is up to 16 m thick but between them its thickness is reduced to 1-2 m. According to Sivan (1996) it was deposited during isotopic stage 6.
5. The Ga'aton Clay Mbr. - Grey to black clay with few marine shell fragments that was deposited mainly north of Akko, probably in a small estuary developed beyond the coastal Regba Kurkar ridge. It is up to 12.5 m thick, but is mostly 3-5 m.
6. The Yasaf Kurkar Mbr. – A shallow marine calcareous limestone that was deposited in a narrow belt along the present coastline. It contains a small amount of Quartz (usually 2-10%) and coarse bioclastic fragments mainly of Calcareous algae. However, in the embayment that existed north of Akko, the calcareous facies passes to dark clay with pelecipodes shells. The thickness of this unit is not more than 1.5 m, and it contains fossils of the gastropod *Strombus Bobinius* LMK, a typical fossil of the Thyranian transgression. According to Sivan (1996) it was deposited during isotopic stage 5.5.

The Holocene period is represented in the Akko area by the Naharia clay of early to Middle Holocene age. In the embayment north of Akko this unit is 5-6 m thick.

## **5. Methodology**

The last time a fault was active can be determined by identifying and dating the youngest stratigraphic or geological marker that was deformed by its activity. The upper time limit to its activity is determined by dating the first geological unit that covers its trace without evidence of deformation. However, the geological and anthropological conditions along the trace of the AFS posed some difficulties in the study of its young activity, because there are no young sediments on the Ahihud Ridge that was already elevated during the deposition of the Kurdani Formation as is evident by the abrasion terrace around its western margins (Fig 5). Therefore, it was subjected to erosion processes at least since the Pliocene. In the coastal plain, which has been under intensive human influence since the middle Holocene, but mainly in

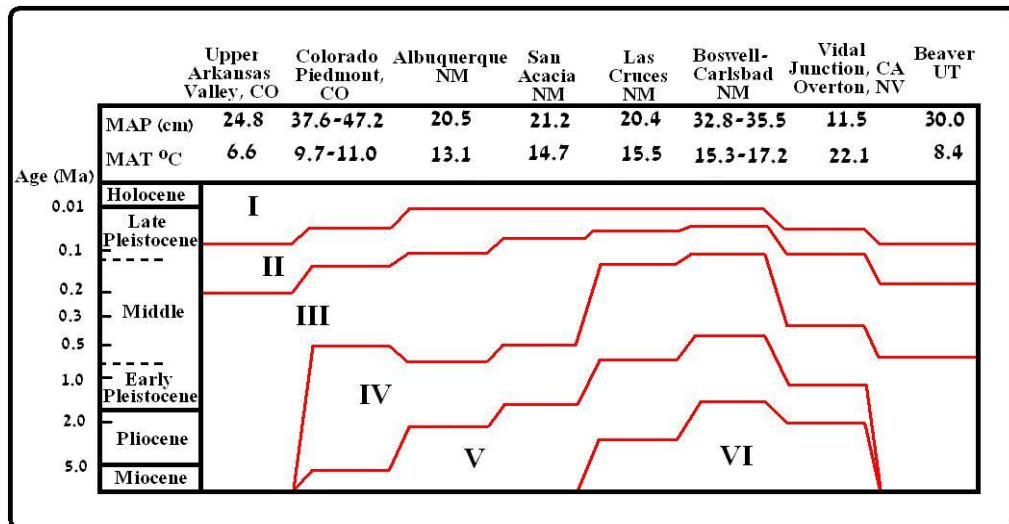
the last hundreds of years, the upper part of the sequence is heavily disturbed by cultivation, infrastructure lines (roads, pipe lines and drainage canals), and buildings (especially in Akko). In fact, the road from Carmiel to Akko is located just above the trace of the Ahihud fault, and therefore, a paleoseismic study is not possible in this area.

An alternative marker for identifying tectonic activity is the extensive cover of calcrete that developed in the Lower Galilee on landscape built of chalk and marl of the Senonian to Paleocene Mount Scopus and the Eocene Avedat groups (Zilberman et al., 2008). Calcrete is a thick calcareous pedogenic crust that is formed by a process of leaching and precipitation of calcite under the upper soil profile. There are several types of calcretes and the type that developed on chalk and marl is termed Nari. This type of calcrete was described by Yaalon and Singer (1974) from the Shefela area, where it is generally 1-3 m thick, built mainly of Bk horizon (the upper massive calcareous part of the calcrete profile) composing of a soft, chalky lower part that became harder toward the upper part.

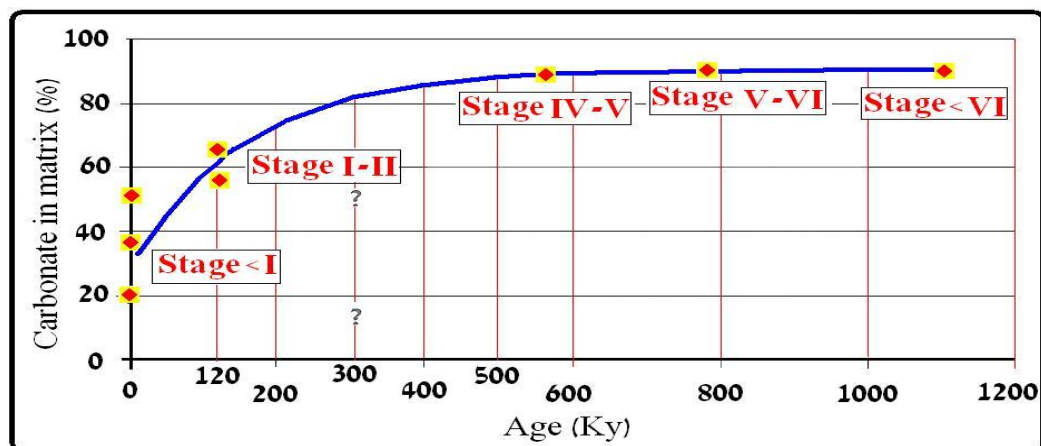
The time required for the development of mature calcrete (stage V-VI according to Gile, 1966, and Machette, 1985) ranges between a few thousand years (Hay and Reeder, 1978) to several hundreds thousand years (Gile et al., 1966; Machette, 1985; Birkeland, 1991) (Fig. 6) and even 1 My (Wright, 1990). In our region, ages of mature calcrete, which developed on slope sediments in the Naftali Mts. (Shtober-Zisu, 2006; Fig. 7) and Mt. Carmel (Mashiah, 2011), are estimated to be several hundreds of thousands of years old. A series of colluvial wedges, well lithified by hard calcrete, were described from one of the marginal faults of the the Bet Kerem Valley by Matmon et al., 2008, 2010). The age of the lithified colluvium units is older than 400-500ka, while the overlying un-lithified colluvial unit yielded an OSL age of  $176 \pm 22$ ka (Matmon et al., 2010).

The rate of calcrete development is highly dependent on the available carbonate supply and the amount of water that percolates through the soil profile, but it is also influenced by the vegetation, especially in Alpha calcrete in the sense of Wright (1990). However, many of the studies about calcrete were carried out in alluvial valleys where it was not always possible to distinguish between ground water calcrete that can precipitated very fast, and slow-accumulating pedogenic calcrete (Wright, 1990). Less is known about the rate of formation of the Nari (calcrete that developed on chalk and marl), where there is an abundant supply of carbonate from the

underlying rock. Most of the Bk of the Nari is formed by re-crystallization of the underlying chalk or marl with additional contributions from dust (Yaalon and Singer, 1974).



**Fig. 6** - Stages of carbonate accumulation and calcrete development in a gravelly sediment in south-west United States (from Birkeland, 1991).



**Fig. 7** - The relations between the age of slope sediments and stage of calcic soil development in the Naftali Mountains, eastern Galilee (From Shtober-Zisu, 2006).

The pedogenic processes of calcrete formation can advance to its final mature stage only upon a stable landscape, which was not subjected to rapid erosion or deposition. Therefore, a widespread mature calcrete cover indicates that the landscape was stable during a long period.

In the Lower Galilee, the regional cover of mature calcrete can serve as a litho-pedological marker for identifying tectonic activity, especially in sites where it covers

fault traces, fault scarps or tectonic induced slope sediments. Therefore, in the present study, we followed the traces of the AFS in the Ahihud Ridge (after Sneh, 2006) to areas where they cross landscape covered by calcrete, and looked for evidence of deformation in these pedogenic units. In the eastern high part of the ridge, which is bounded in the south by the northern Judeida fault the slopes are built of hard Cenomanian-Turonian carbonates, with no calcrete crust. However, a thick colluvium unit is attached here to the southern tectonic slopes of Har Gamal (Zilberman et al., 2008). The section of this colluvium, which is exposed in a small quarry, is cemented by a thick (at least 5 m) calcrete unit. Since the rate of deposition of colluvium along the foot of a tectonic escarpment is highly dependent on the rate of tectonic activity and the growing fault escarpment ( McCalpine, 1982; Nelson and McCalpine, 1991; Lettis and Kelson, 1998), this well-developed calcrete suggests a long period of stability with a small contribution of slope debris.

We estimated the ages of the calcretes in the study area using paleomagnetic analyses, which was found as a reliable dating method for calcretes that cemented colluvial units in the Bet Kerem area (Matmon et al., 2010) and Mt. Carmel (Mashiah, 2011). Sixty one oriented samples were taken from the calcrete profiles using small boxes in soft lithology or drilled cores in the hard parts of the Bk horizon. 3-5 samples were taken from each sampling point. Paleomagnetic experiments were carried out at the paleomagnetic laboratory of the Institute of Earth Sciences, in the Hebrew University of Jerusalem, using a 3-axis 2G cryogenic magnetometer with an integrated alternating field (AF) demagnetization unit, and ASC-TD-48 thermal demagnetizer oven. Fifty-five samples were demagnetized to a peak field of 40 mT in steps of 5 mT or 10 mT. In addition, three cores from Har Gamal were split into two specimens – one was AF demagnetized, and the other was thermally demagnetized in steps of 100°C, 50°C and 30°C to 330°C. Best-fit directions of the paleomagnetic vectors were calculated by the principal component analysis method (Kirschvink, 1980), using the PmagPy software (Tauxe, 2010).

The magnetization was transformed to age using the chronology of the geomagnetic polarity time scale (Gradstein et al., 2004). Our basic assumption is that the magnetization of the calcrete was acquired by pedogenic processes associated with the calcrete formation. Hence, the paleomagnetic polarity provides relative time constraints for the age of the calcrete formation.

## 6. Results

Three study sites were selected for paleomagnetic sampling of calcretes (Fig. 2): The calcrete that covers the trace of the southern Judeida fault (after Sneh, 2006), was sampled in the Amin Tarif forest (coords. 21575/ 75775). The calcrete that developed on the colluvium unit attached to the northern Judeida fault was studied and sampled along the southern slopes of Har Gamal (coords. 21910/ 75765), and the calcrete that covers the trace of the eastern part of the Ahihud fault was examined and sampled west of the Akko cemetery (coords 21270/75770).

### 6.1 Har Gamal Mountain site (The northern Judeida Fault)

Har Gamal, which is the highest point in the Ahihud Ridge, is part of the northern uplifted block of the northern Judeida fault. In this area the fault displaces the lower part of the Bina Formation versus the top Menuha Formation, a displacement of more than 100 m. It is assumed that the fault runs along the contact between the steep southern slopes of Har Gamal, which are built of hard, bedded limestone of the Bina Formation, and the gentler surface of the colluvium apron.

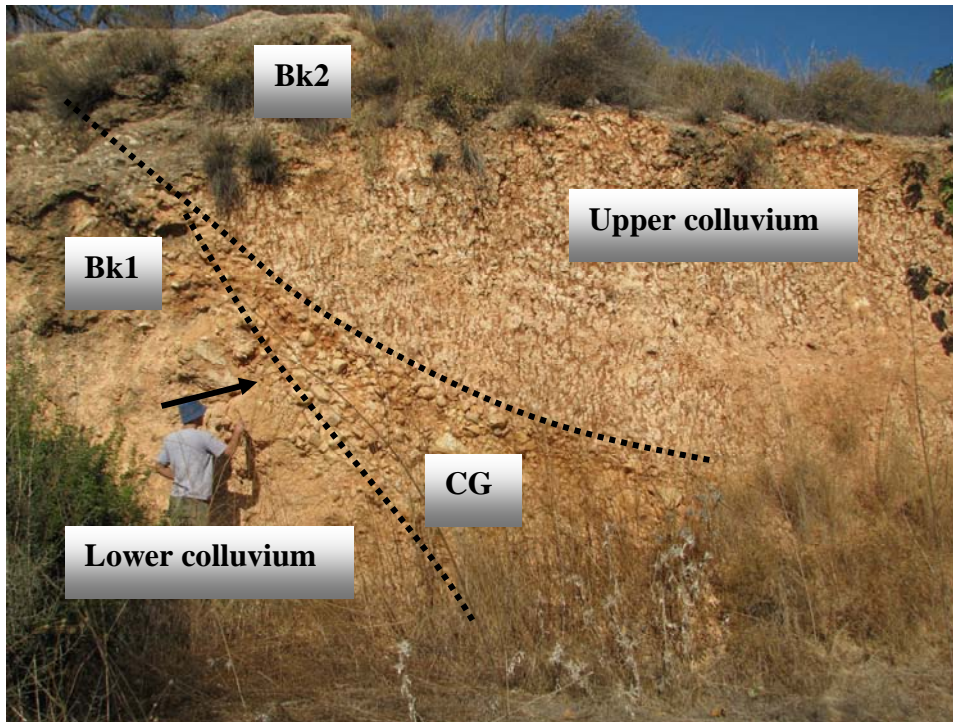
Two colluvial units, each cemented by mature (stage IV-V) calcrete, are exposed in a small quarry located at the lower part of the colluvial slope (Figs. 6, 7). The contact between the two colluvial units is exposed in the western part of the quarry. The upper colluvium fills a wide channel incised in the lower colluvium. The channel wall is covered by clast-supported, coarse gravel colluvium, cemented by carbonate.

**The lower colluvium** is about 4 m thick (base is not exposed) and is cemented by stage IV-V calcrete, with hard brown Bk horizon at top. The upper part of its Bk was mostly eroded but preserved as angular blocks embedded in the base of the coarse gravel colluvium that accumulated on the channel wall (Fig. 6).

**The upper colluvium** builds most of the quarry wall. It is at least 5 m thick (Base is not exposed) cemented by stage IV calcrete (Fig. 7). The lower 3 m of the section is built of mottled, chalky calcrete with a bit of coarse gravel embedded in the calcareous matrix. Remains of reddish soil are preserved between the coalescence calcareous nodules (Fig. 7).

Upward, a weak laminar texture developed in the soft chalky matrix and the reddish soil patches disappear. The upper Bk horizon is 1-2 m thick, built mainly of a nodular carbonate with a hard calcareous limestone (20-30 cm) at its top (Fig. 8). Although a

preliminary karstic relief is developed on the exposed Bk horizon (Fig. 8), it is generally well preserved and mostly coated by a laminar crust (Fig. 9).



**Fig. 6** - *The contact between the lower and the upper colluvial units in Har Gamal. The upper colluvium fills a channel incised into the lower colluvium. A coarse gravel colluvial unit (CG) accumulated on the channel wall before the deposition of the upper colluvium. Eroded blocks from the Bk of the lower colluvium (Bk1) are marked by the arrow. The Bk of the upper colluvium (Bk2) covers the entire surface.*

At some places near the quarry, where the Bk is exposed, it is incised by shallow channels (up to 20 cm deep), which are also covered by a thin, brown calcareous crust. Further to the west, where the Ahihud Ridge is built of Chalk of the Mount Scopus group, the slopes are still covered by silty loam underlain by a well-preserved calcrete crust.



**Fig. 7-** *Paleomagnetic sampling in the lower part of the upper colluvium unit in the quarry at Har Gamal.*

### **6.1.1 Paleomagnetic results**

Three oriented cores were drilled below the contact between the lower and the upper colluvium and three oriented cores were drilled right above the contact (Table 1, Fig. 6). Twenty-eight oriented boxes were sampled from five different horizons in the soft upper calcrete (Table 1, Fig. 7). Nine oriented cores were drilled from three different levels in the upper colluvium hard calcrete, (Table 1, Fig. 8). The lower part of the Bk horizon of the upper colluvium calcrete (about 2 m) was not sampled due to technical difficulties raised by the nodular texture of the calcrete. All specimens (total of forty specimens) have a stable magnetization, thirty-nine of which show northerly normal polarity, while one sample shows an anomalous direction (Fig. 15). The results clearly indicate normal paleomagnetic polarity.

Table 1 – Paleomagnetic results from Har Gamal colluvial units.

Sample	Ah1	Ah2	Ah3	Ah4	Ah5	Ah42	Ah6	Ah7	Ah40	Ah41
Sampling method	Oriented Box (OB)	OB	OB	OB	OB	OB	Oriented core (OC)	OC	OC	OC
Unit	Up.col.	Up.col.	Up.col.	Up.col.	Up.col.	Up.col.	Up.col.	Up.col.	Low.Col.	Up.Col
Stratigraphic level	0.3 m	0.9 m	1.2 m	1.7 m	2m	3m	Top Bk	Top Bk	Below contact with Up. Col.	Above contact with Low. Col.
Number of samples	4	3	4	4	3	2	7	6	3	4
Paleomagnetic polarity	N	N	N	N	N	N	N	N	N	N



**Fig. 8** - Sampling site at the hard top of the BK horizon of Har Gamal calcrete. Notice the undeveloped karstic relief.



**Fig. 9** - *The laminar crust (partly eroded) on top of the Bk horizon of the upper colluvium calcrete.*

### **6.1.2 Summary and discussion**

The two colluvial units and the associated calcrete profiles attached to the tectonic southern slope of Har Gamal, represent seven stages of development:

1. Deposition of the lower colluvium.
2. Development of stage V calcrete on a stable slope.
3. Deep erosion (at least 4 m) of the colluvium and the calcrete.
4. Deposition of a coarse gravel colluvium on the channel wall.
5. Deposition of the upper colluvium, which is composed mostly of fine clastic sediments.
6. Development of Stage IV calcrete in the upper colluvium
7. Exposure of the Bk of the upper colluvium and initiation of sub-aerial weathering.

Although the two calcretes in Har Gamal preserve a normal paleomagnetic signal, it is difficult to compress the above seven stages in the Bruhns normal magnetic chrone that started before 780.000 years. However, since the lower colluvium was sampled in only one site, which was located very close to the erosional contact with the upper colluvium, its normal signal should be treated consciously.

Rapid accumulation of colluvium along the foot of tectonic escarpments is usually interpreted as a proxy for tectonic activity, while development of a mature soil profile on the colluvium is associated with a long stability period (Wallace, 1977; Hank, 1984; Mayer, 1986; Forman et al., 1991; Gerson et al., 1993; Amit et al., 1995). The change of the scarp profile with time due to degradation is also used to estimate the past tectonic activity of faults, applying a scarp degradation model based on the diffusion equation (Nash, 1980, 1987; Mayer, 1984; Enzel et al., 1996).

However, the slope degradation models and the study of fault escarpment colluvial sediments were mostly applied to fault scarps in unconsolidated sediments, where the free face of the scarp is rapidly modified by erosion (at the upper part) and deposition (at its lower part). These models cannot be applied to tectonic mountain fronts built of hard bedrocks such as carbonates (Stewart, 1993) or crystalline rocks (Menges, 1990). In these slopes the transition between weathering-limited (exposed) or transport-limited (covered by soil and colluvium) slopes is highly influenced by the geometry of the slope, the bedrock type and climatic fluctuations with time (Menges, 1990; Howard and Selby, 1994).

Since each of the two mature calcrete profiles of Har Gamal represents a long developing time, probably of a few hundreds of thousands of years, it seems that the long-term pedogenic processes in this site were not sensitive to the rapid middle and late Pleistocene glacial-interglacial climatic fluctuations. The same is true for the two episodes of colluvium deposition, and the single erosion event that separates them.

The alternative options are: 1. The stratigraphy of the colluvial sequence represents only extreme climatic events, and 2. each of the colluvial units reflects a tectonic event followed by erosion of the fresh scarp.

The tectonic interpretation is at odds with evidence of a long term stability of the Ahihud Ridge, manifested by the low altitude (30-40 m) of the abrasive surface of the Kurdani Formation at the western part of the ridge, which match the maximum Pliocene sea level (Miller et al., 2005) . The tectonic interpretation is also challenged by the nature of the slope processes presented by the colluvium stratigraphy. The deep incision in the lower colluvium was followed by refill of the incised channel by the upper colluvium just up to the previous surface of the slope. This was not possible if the incision was triggered by a tectonic activity that increased the topographic separation between the slope and the near valley. Therefore, sedimentation and erosion processes in the colluvial apron of Har Gamal, seems to react to major climatic events rather than to rejuvenation of tectonic activity.

Weather tectonic or climatic forces triggered the main slope process in Har Gamal, the mature calcrete that developed on the upper colluvial unit as well as on other parts of the slope, indicates a long stability period, at least 100 ka long, but probably much longer.

## **6.2 The Amin Tarif Forest sampling site (The southern Judeida fault)**

The Amin Tarif forest site is located on the eastern part of the southern Judeida fault, as it appears on the map (Fig. 2). According to the geological map by Sneh, (2006), the trace of the fault crosses here a shallow hill (Trig. Point 83) displacing the Eocene Timrat Formation on the north-eastern side versus the Santonian Menuha Formation on its south-western side.

During this study we found that this hill is covered by a thick calcrete of the Nari type with a Bk horizon up to 3 m thick. The continuous un-deformed cover of the Nari prevents any possibility to locate the exact position of the fault trace in this area. The Bk horizon is fractured and has a remarkable karstic relief, indicating a long time of exposure to weathering processes. A section of the Nari is exposed in a small NW oriented abandoned stream valley elevated 20-30 m above the present west-flowing drainage system in the nearby Zevulun valley. The stream incised the thick Nari that today is only preserved on its slopes."

### **6.2.1 Paleomagnetic results**

Nine oriented cores were drilled from the lower, middle and upper parts of the 2.3 m thick Bk Nari outcrop (Fig. 10; Table 2). The behavior of the samples in the demagnetization experiments resembles the behavior of the samples from Har Gamal, showing a stable magnetization. However, the direction of the magnetization is puzzling. Samples are expected to have northerly (or southerly) directions with a positive (or negative) inclination of  $46^\circ$ , depending on the polarity of the field. Yet, only one sample shows this behavior. Five samples have a magnetization pointing NW with a negative inclination, and three samples have a northerly magnetization but with steeper inclinations than the expected inclination (Fig. 15). The four samples that have a northerly magnetization and positive inclination are from the lower and the middle part of the outcrop. Normal polarity is the preferred and most plausible interpretation, but it should be taken with caution. Further sampling is required for final determination of the paleomagnetic polarity.



**Fig. 10** - *The Bk horizon at the Amin Tarif Forest site*

Table 2 – Paleomagnetic results from Amin Tarif forest.

Sample	TA01	TA02	TA03
Sampling method	Oriented Core (OC)	OC	OC
Stratigraphic level	Lower Bk	Middle Bk	Upper Bk
Number of samples	3	3	3
Paleomagnetic polarity	?	N	?

### **6.2.2 Summary and Discussion**

Although, there is no information about the time required to develop a 2-3 m thick Bk horizon on soft carbonate rocks (Nari), it is clear that such a process can take more than 100 ka (Zilberman et al., 2008). To this estimation one should add the time that elapsed since this Bk horizon was exposed to sub Aerial weathering processes that formed the karstic relief on its surface.

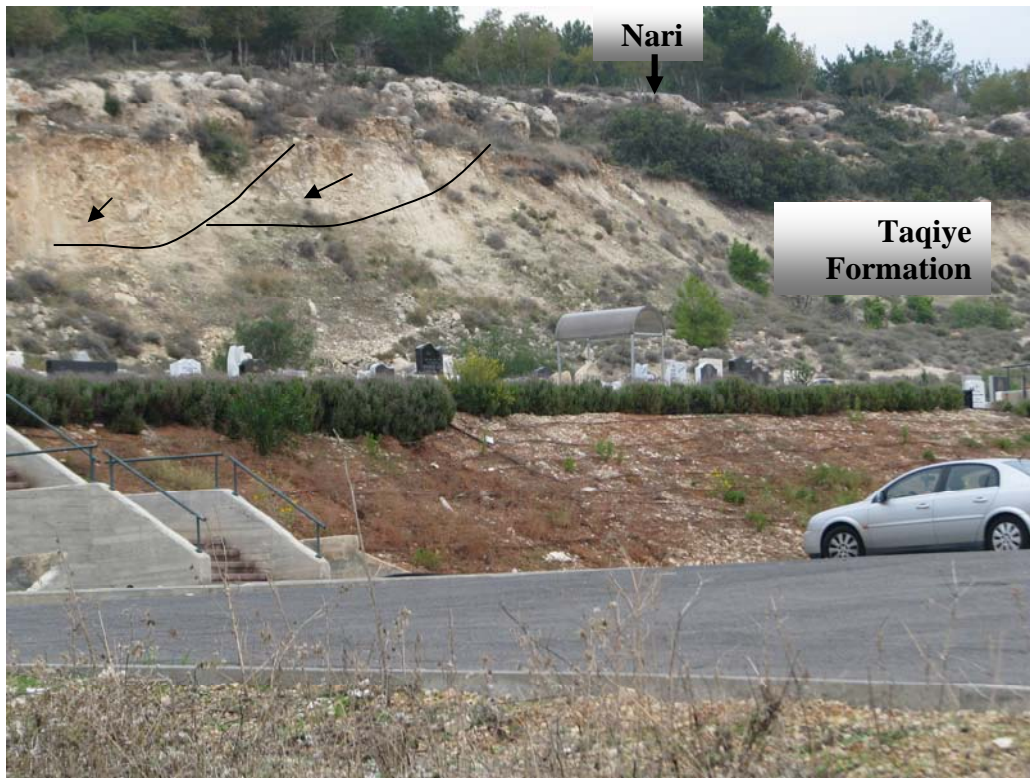
If the erosion of the Nari along the abandoned valley in the Amin Tarif forest is related to the incision of the now-abandoned stream, it means that it was already well developed when the stream was active. This assumption pushes the time of its formation back to the Pliocene, when the coast was located along the western margins of the Ahihud Ridge, and the present west flowing drainage system was probably 20-30 m higher than today.

However, the possibility that the Nari was removed artificially from the valley in order to expose the underlying soft rocks for agricultural purposes should also be considered. Yet, in this scenario we expect to find many residual calcrete fragments that remained from the excavation. Such remains were not found in the abandoned valley. Since the Nari that covers the extrapolated trace of the southern Judeida fault (as it is marked in the geological map) was found un-deformed, we conclude that this fault has not been active at least since the late Pleistocene.

### **6.3 The Akko cemetery site (the Ahihud fault)**

The eastern exposed trace of the E-W oriented Ahihud fault runs along the southwestern part of the Ahihud Ridge displacing the Paleocene Taqiyeh Formation on its northern part so that it appears alongside the Eocene Timrat Formation (see Shefar'am sheet geological map of 1:50.000). The Akko Cemetery is located in an old quarry excavated across the eastern trace of the mapped fault. This quarry exposed a sequence of the Taqiyeh Formation overlain by slumping blocks of the lower part of the Eocene Adulam Formation (Fig. 11). The hill top is covered by an undisturbed Nari crust 1-2 m thick. The western part of the mapped fault runs along the foot of the southern slope of the Ahihud Ridge. This slope separates between a flat abrasive terrace capped by the shallow marine Kurdani Formation in the north (altitude of 30-40 m) and the Zevulun Valley in the south (altitude of 10 m).

The eastern part of this slope is covered by a continuous thick Nari crust that developed on chalk with chert nodules, typical of the Maresha or Adulam Formations (Fig 12). However, there is no fresh exposure of the sequence and therefore it is not clear if this sequence is insitu or it consists of slumped blocks, as exposed in the nearby quarry. The Nari is weathered showing karstic relief on its Bk horizon (Fig. 12).



**Fig. 11** - *The Akko Cemetery. It is located in a quarry, which exposed the soft grey marl of the Taqiye Formation that is overlain by slumped Eocene blocks (marked by arrows).*

Farther to the west, two steps appear in the Nari crust and they converge further westward to a single fresh looking morphological step devoid of a Nari cover (Fig. 13). This slope also appears on an aerial photo taken in 1945 (PS series), separating between the cultivated Zevulun valley in the south and the slopes of the Ahihud Ridge in the north.

### **6.3.1 Paleomagnetic sampling**

Twelve oriented cores were drilled in the continuous Nari covering the slope descending from the abrasive surface of the Kurdani Formation to the Zevulun Valley (Table 3). Nine cores were drilled in the exposed sequence of the Bk horizon at the middle part of the slope (Table 3; Fig. 14), and three cores were drilled in the hard top of the Bk horizon at the lower part of the slope, where the mapped fault trace is supposed to run. All the samples show a stable magnetization with normal polarity. The magnetizations are well grouped around the expected GAD direction, indicating the stability of the slope (Fig. 15).



**Fig. 12** - *The southern slope of the Ahihad Ridge west of the Akko cemetery. The slope is covered by an undisturbed Nari crust with karstic relief.*

**Table 3** – The Akko Cemetery Site

Sample	BK01	BK02	BK03	BK04
Sampling method	Oriented Core (OC)	OC	OC	OC
Stratigraphic level	Middle slope Bk - Lower Part	Middle slope Bk – Middle part	Middle slope Bk – Upper part	Top of Lower slope Bk
Number of samples	3	3	3	3
Paleomagnetic polarity	N	N	N	N



**Fig. 13** - A "fresh-looking" slope at the assumed trace of the Ahihud fault at the western edge of the Ahihud Ridge.



**Fig. 14** - Sampling the Nari at the middle part of the slope west of the Akko cemetery.

### **6.3.2 The Akko Cemetery site - Summary**

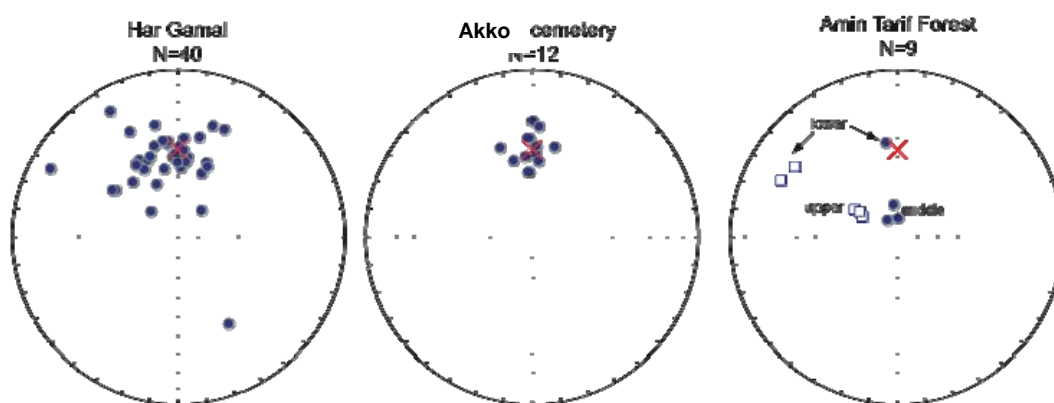
The vertical displacement of the Kurdani Formation along the Ahihud fault is estimated as 70-80 m (Kafri and Ecker, 1964; Sivan, 1996). To this displacement that formed the Hillazon Graben, one should add the 20-30 m vertical differences between the abrasion surface of the Kurdani Formation on the Ahihud Ridge and the surface of the Zevulun valley. The slope that separates between these two surfaces is of tectonic origin and it post dated the formation of the adjacent abrasion surface of the Plio-Pleistocene Kurdani Formation. The undisturbed calcrete, with a normal magnetic signal that covers the eastern part of this slope, indicates a long stability period along the eastern tip of the fault at least since the Middle Pleistocene. However, this calcrete appears to be displaced in the western part of the slope, where a calcrete free escarpment runs along the southern foot of the ridge. Although this escarpment is at least 56 years old (Since the PS airphotos were taken), it is not clear yet if it is of a tectonic or an artificial origin. This question can only be solved by trenching this step.

### **7. The Ahihud Ridge fault system - Summary and conclusions**

The goal of the present study was to look for evidence of recent tectonic activity or long term tectonic stability along the Ahihud tectonic ridge. Three faults were examined in this area: The two Judeida faults and the Ahihud fault. From a geometric point of view, the two NW oriented Judeida faults can be considered as part of the Bet Kerem fault system (Matmon et al., 2000), while the Ahihud fault is part of the E-W oriented fault system that underlies the northern coast of Israel (Mero, 1983, Sivan, 1996).

The present study found that the two Judeida faults have not been active at least since the late Pleistocene, and probably even earlier. However, the Ahihud fault was probably active after the formation of the calcrete crust that paves the southern slope of the Ahihud Ridge. The normal paleomagnetic signal found in this calcrete suggests that it developed during the Bruhns normal magnetic chrone, in the last 780.000 years or in the previous Gause chrone (2.58-3.58 Ma). It is not possible yet to determine when this pedogenic calcareous crust was exposed from the soil cover and its development terminated. The karstic relief that developed on the exposed calcrete suggests that it has been exposed for a long time, but this period can not be estimated because there is no information regarding the rate of surface leaching of calcareous rocks in a Mediterranean climate.

However, additional information about the upper time boundary for calcrete development in this area can be obtained from a series of six colluvial units attached to the near (10 km eastward) Zurim escarpment (Matmon et al., 2008, 2010). The upper 150-200 ka old colluvial unit of this series did not develop any clear calcic soil profile, while the underlying older (>400-500ka) colluvial units are well cemented by mature calcrete. This might suggest that in this area the late Pleistocene period was not associated with calcrete development. Considering the time required to develop a mature calcrete profile, it is possible that some of the well cemented colluvial units attached to the Zurim Escarpment have developed in the Gauss normal chrone.



**Fig. 15** - Equal area projections of the paleomagnetic mean vectors (total of 61 specimens). Positive inclination is marked as solid circles. Negative inclination is marked as open squares. Red 'X' marks the time-average normal geomagnetic vector (i.e. the geomagnetic axial dipole - GAD vector) in Ahihud area. All samples from Har Gamal (excluding one outlier) and Akko cemetery show northerly normal-polarity paleomagnetic directions scattered around the normal polarity GAD vector. Paleomagnetic vectors from the Amin Tarif forest fall far from the GAD vector (see text for discussion).

The conclusion that stems from this assumption is that most of the present relief of the Ahihud Ridge and the Zurim escarpment was already established at the end of the Pliocene. This stability is also evident by the morphological position of the coastal abrasion surface of the Kurdani Formation at the western part of the ridge. The Pliocene transgression sea levels were not higher than 25-30 m (Miller et al., 2005), indicating that this abrasive surface located at altitude of 30-40 m, preserves the original position of the coastline. Since the relief of this ridge is of tectonic origin, it

can be estimated that the rate of tectonic activity during the Pleistocene along the Judeida faults was very low. However, Pleistocene tectonic activity did occur along the Ahihud fault, where the Hillazon Graben was subsided some 80 m after the deposition of the Kurdani Formation (Kafri and Ecker, 1964, Sivan, 1996). If the calcrete-free morphologic escarpment along the eastern part of the Ahihud fault is of tectonic origin, a paleoseismic study in this site has the potential to shed more light on the Pleistocene tectonic activity along this fault.

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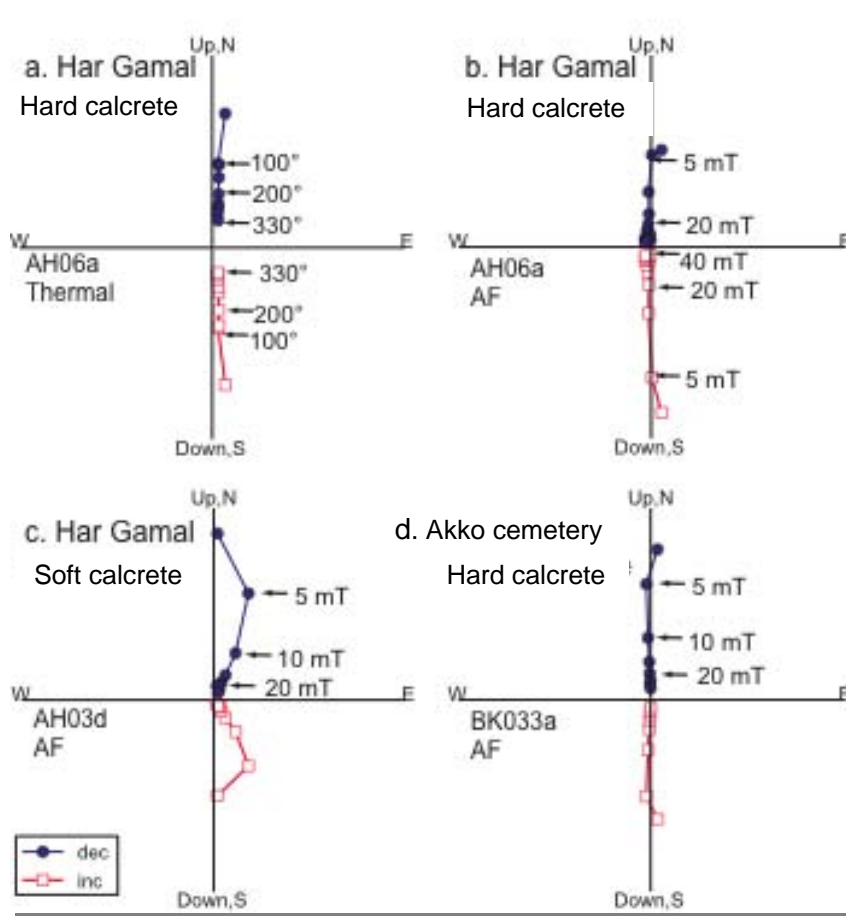
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## 9. Appendix



*Representative orthogonal plots of demagnetization experiments. a,b) Thermal and AF demagnetization of the top Bk hard calcrete, Har Gamal. c) AF demagnetization of the soft calcrete, Har Gamal, d) AF demagnetization of hard calcrete, from Akko cemetery (Ahihud).*